Coherent Optical CDMA Networks

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Abstract—**Recent work in optical code division multiple access (CDMA) is reviewed, progressing from incoherent to coherent techniques. It is shown that under appropriate conditions, coherent CDMA can in principle rival wavelength-division multiplexing (WDM) in terms of aggregate network throughput. Furthermore it is shown that at high data rates, some of the components for WDM and coherent CDMA networks are nearly identical, indicating a similarity between the two approaches. CDMA retains a coding aspect which may prove attractive in security applications.**

I. Introduction

Anticipated requirements for future multiple access local area networks (LAN's) are of the order of 1 Gb/s per user, and hundreds of simultaneous transmissions, for an aggregate throughput of the order of 1 Tb/s. Recent developments in coherent optical CDMA indicate that it is a possible means of meeting these requirements. While WDM has received much attention in recent years as a possible solution, it is not without problems; in particular changing addresses is difficult, as it requires precise tuning of either transmitting laser, or receiving tuned filter or local oscillator. Hence studying alternate multiple access schemes is justified. The object of this paper is to review the work on optical CDMA, and to study the main features characterizing incoherent and coherent CDMA. It will be shown that in order to make possible the implementation of optical multiple-access networks with aggregate bit rate in the Tb/s range, coherent CDMA would have to be adopted. A major advantage of doing so is that changing addresses can simply be accomplished by changing a set of phases, which requires a relatively simple encoding/decoding network at each station, unlike the very complex network reconfigurations required for incoherent CDMA. In that situation, if fiber ladder networks are used, then the configuration of the decoders is remarkably similar to that of the concatenated Mach–Zehnder interferometers used in WDM (or FDM) networks [1].

This fact indicates that coherent CDMA and WDM techniques may converge at high data rates. To verify this, a comparison of the potential of these schemes from the points of view of aggregate bandwidth, signal-to-noise ratio, and hardware requirements, will be performed. It will be shown that CDMA can be competitive with WDM provided that either very short (subpicosecond) pulses are used, and a very fast optical thresholding device is available to select the autocorrelation peaks, or that a reference pulse is sent along with the encoded pulse.

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The possible advantageous security aspects of optical CDMA networks will be described.

II. Incoherent Signal Processing with Fiber-Optic Delay Lines

The advent of long low-loss optical fibers in the early 1970's provided a new means for making delay lines with characteristics exceeding those obtained with surface acoustic wave (SAW) devices. Consequently some work was done to demonstrate the performance with optical delay lines of operations previously performed with SAW devices [2]–[4]. Fibers were used to split, delay, and recombine short optical pulses, thus generating impulse responses consisting of trains of pulses. By cascading such arrangements, the auto- or cross-correlation of such pulse trains could be achieved. In particular, Marom introduced a ladder network formed by cascaded 2 × 2 couplers [4], which was used for several other purposes later on. In these investigations, the operations were performed on an incoherent basis, i.e. it was assumed that addition of power occurred.

This type of work culminated in the mid-1980's at Stanford University, where rather sophisticated signal-processing operations were performed in ladder networks, used again on an incoherent basis [5].

While the above work used transmissive fiber-optic components, analogous studies were also performed with reflective arrangements [6].

III. Incoherent Optical CDMA

In the mid-1980's it was then proposed to use this type of optical signal processing to implement multiple access optical networks with asynchronous transmission. The idea was to extend to the optical regime the techniques of pulse coding and spread spectrum which are so successful at radio frequencies [7]. A major difference is that while the rf techniques are coherent, the initial optical work was incoherent.

A. Main Features

In incoherent optical CDMA the phases of the light signals are not important, as they are summed on the basis of power, rather than electric field. In all passive schemes, the encoder uses a passive optical network to generate an impulse response which is a train of P pulses, delayed scaled replicas of the input laser pulse (which are called chips). If the chip duration is τ_c, the duration of a coded sequence corresponding to a bit is $L\tau_c$, where L is an integer. At the receivers specific sequences are recognized by performing the operation of correlation with other sequences. Several schemes have been proposed to implement the correlation.

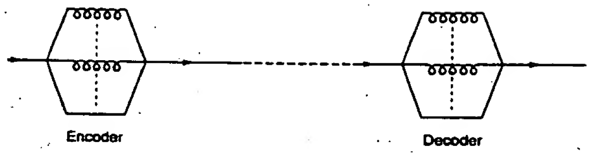


Fig. 1. CDMA encoders and decoders based on power splitting and combining by means of $1 \times P$ and $P \times 1$ splitters and combiners.

In one approach, an optical pulse sequence is multiplied by the stored signal, presumably by means involving the use of a fast optical modulator, or switch, and the detected result is integrated over a bit time by electronic means [8]. The multiplication proceeds in real time, i.e., the modulator must act during a chip time, and the two sequences must be synchronized to less than a chip time. Clearly these requirements become very difficult to implement as the chip time becomes very short. Furthermore, it can be argued that if one is successful in doing these things, then one has available a very fast, high contrast switch which would perhaps be used more effectively in TDMA, or in a switching network.

The other approach is a more completely optical one, which does not suffer from the argument raised above. Here an actual correlation is performed by optical means only. A typical approach for encoding and decoding bits in this case is shown in Fig. 1. Each network, encoding or decoding, is built in such a way that a short pulse incident in its input fiber results in a pulse train, the respective impulse response, coming out of its output fiber. As a result, when an impulse is fed into the encoder, the decoder output is the correlation, performed directly in the time domain, between the impulse responses. Since the signals here correspond to power, they are always positive, and so are the correlation signals. This approach is appealing in the sense that it produces a correlation signal in real time which can be used for matched decoding, by looking at the peak of the correlation: an input signal matched to the decoder yields a relatively high autocorrelation central peak, which can be detected by means of a fast threshold detector.

Fairly complete studies have been performed on networks based upon this principle [9], [10]. The basic idea for a multiple access network based on this approach is to have the ability to change codes at will in order to address particular receivers. While the concept is simple, there are substantial practical difficulties when trying to reduce it to practice.

B. Limitations

1) *Power budget:* While networks such as shown in Fig. 1 can generate arbitrary pulse sequences, and hence codes with interesting properties, such as (pseudo) orthogonality, they turn out to be rather inefficient from the point of view of utilization of optical power. If the number of chips in a sequence (code weight P) is large, then the encoding process leads to a loss in total bit energy by a factor of P.

In order to alleviate this difficulty we have studied the use of fiber optic ladder structures, Fig. 2, for optical CDMA. An n-stage network consists of $(n+1)$ fixed 3-dB couplers connected in cascade by n double fiber links. With these networks, the encoder total bit energy reduction is only a factor of 2, regardless of $P = 2^n$ [10].

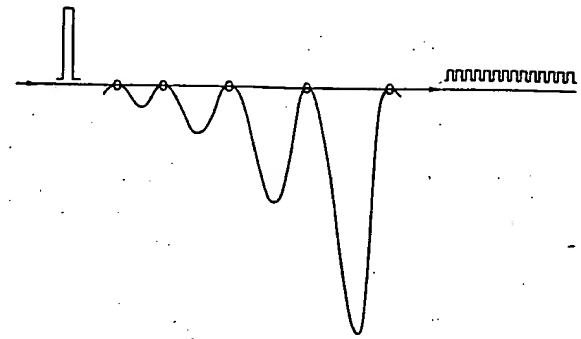


Fig. 2. CDMA encoder based on a ladder network made from cascaded 2×2 couplers.

Considering now the amplitude of a matched autocorrelation peak compared to the original energy fed into the encoder, we find that it is down by a factor of P^3 for prime networks, but only $4P$ for ladder networks. These expressions correspond to ideal components, with no excess loss. When realistic components are considered, the advantage of the ladder approach is reduced, since in it the losses add up linearly; nevertheless, for moderate values of n, a substantial advantage remains [11].

We have studied in detail the optical properties of networks based on ladder networks. We have also shown that the kind of sequences which can be generated from these networks are sufficiently flexible as to yield overall system performance comparable to that of the more versatile (code-wise) networks of Fig. 1 [10]. These ladder networks thus provide an interesting new approach to the all-optical synthesis of encoders and decoders for incoherent CDMA.

2) *Sidelobes:* A corollary of having a relatively low autocorrelation peak is that the rest of the energy must be spread over sidelobes, which are distributed over an interval of length $2L$ centered around the autocorrelation peak. In incoherent CDMA, regardless of the architecture of the coding network, the ratio of total energy in the sidelobes over energy in the peak of the autocorrelation is $(P-1)$. Even for codes with moderate weights, much more energy is spread in the rest of the bit, compared to the useful autocorrelation peak. This is not only a waste of energy for the autocorrelation peak, but also a large amount of useless power spread over the bit time, i.e., noise contributing to interference with other autocorrelation peaks, and hence lowering signal-to-noise ratio, and increasing bit error rate (if one attempts to space bits by less than $(2L-1)$).

3) *The addressing problem:* This problem may actually be a more serious difficulty for the practical implementation of incoherent CDMA networks than the power considerations. By addressing problem we refer to the need for each transmitter to be able to modify its encoder quickly to generate the suitable code sequence to reach particular destinations. Ideally, each transmitter should be able to reach each receiver.

The approach proposed for all-optical incoherent CDMA encoders has been to have at each transmitter a vast array of delay lines available in parallel, and to reconfigure these appropriately by means of switches to create all desired

sequences [9]. If one examines in detail the requirements for a network of moderate size, it is found that the number of individual delays and switches is very large.

We have introduced a somewhat better method, particularly suited for ladder networks, but it still requires each transmitter to have in parallel all the possible encoding networks. Adding to this the cost of the required fast switches makes for a total cost which is probably out of line with whatever benefits might be derived. Going to shorter chip time will of course greatly reduce the fiber length requirement, but will not help with the switching problem.

An interesting new approach, a reconfigurable ladder network, has recently been proposed [12]. It looks like Fig. 2, except that the 2 × 2 couplers are now variable, and can be changed into 3 dB couplers, or switches. With this approach, many codes can be generated without having to use parallel fiber networks. On the other hand, the excess loss and crosstalk of optical switches may cause other problems when trying to implement this in practice, especially with large code lengths.

4) *Short pulses:* Going to shorter chip and bit durations is a desirable goal from the point of view of the last argument, and of course in general it would help to increase the aggregate throughput of the total broadcast network. As long as one has to detect the optical signals with some kind of an optoelectronic device, and deal with the resulting electrical signals by means of electronic amplifiers, filters, etc., it appears that τ_c of the order of 100 ps could be considered state of the art today, and might eventually end up being about 10 ps. Going to femtosecond optical pulses would not be realistic because the electronics could not follow, but it could be done by using fast nonlinear optical elements, such as based on the Kerr effect, before the electronics; in fact we will show later on that this is the regime where CDMA can best compete with WDM.

Looking then at optical pulses in the picosecond range, we must now see whether they could be considered to be incoherent when superimposed after delays. That depends on the laser source. For instance if one uses the popular Nd-YAG laser, and mode-locks it to produce pulses of the order of 100 ps length, one finds that these pulses are essentially transform limited, i.e., the pulse length is of the order of the reciprocal of the gain bandwidth, which is itself the coherence time. In other words, such a laser will emit short pulses, but each one will exhibit a great degree of temporal coherence, and will strongly interfere with itself after any delay still leading to pulse overlap. With such a light source, it will not be possible to observe incoherent superposition of pulses as sometimes assumed, but rather one will observe coherent superposition.

While it is clearly possible to find laser sources which will still behave to a good approximation as temporally incoherent sources in the picosecond regime, the use of short pulses will rule out more sources, and will make the aspect of coherence a more difficult one, thereby aggravating further the design of incoherent CDMA networks.

At this point it thus becomes a natural question to ask whether it worth trying to preserve incoherence for dubious advantages, or whether one should in fact go in the opposite direction, that of full coherence, or at least partial coherence, and see whether significant benefits might not be derived that way.

IV. Multivariate Incoherent Optical CDMA

In the preceding section we have described incoherent CDMA wherein a single fiber emerges from each encoder, and the encoding is done by generating temporal sequences of chips in that fiber. As we have seen, this requires combining optical signals, with possibly high losses. Another approach, multivariate CDMA, considers the possibility of using several fibers in parallel through the entire system, with an equal number of broadcast networks in parallel as well. This was first proposed by Hui [13], and then pursued by a group at the University of Southern California [14], [15]. This approach has a number of advantages: by avoiding combining at the encoders, it is optically efficient; it provides coding flexibility; the addressing and sidelobe problems are relaxed.

It is beyond the scope of this paper to compare single-fiber and multivariate CDMA. In what follows incoherent CDMA will refer to the single-fiber type.

V. Coherent Optical CDMA

Some of the limitations encountered in incoherent CDMA can be traced to the use of power summation, as opposed to field summation in the case of the successful rf techniques. It is thus worth investigating whether coherent optical CDMA, a better parallel to the rf techniques, could be implemented with beneficial results. Since coherent superposition is phase sensitive, the use of such techniques will of course be more difficult than that of incoherent ones, because of the need to provide adequate optical phase control and stability; on the other hand, if phase can be controlled adequately, then it should add new dimensions to the design of optical CDMA networks, with potentially very beneficial results. The first proposals to use coherent CDMA with fiber encoders, and the first initial demonstrations, were made with ladder networks, by two separate groups [16]–[18].

In coherent CDMA one still has the same basic network and temporal (envelope) pattern for the impulse responses as in incoherent CDMA, but now in the optical correlation process the pulses are summed up coherently, by having a light source with a coherence length greater than the chip length. The phases of the individual pulses coming out of the encoder, and those experienced when going through the decoder, strongly influence the interference and hence the resulting pulse amplitudes.

The correlation process thus yields the same pulse locations as in incoherent CDMA, but the amplitudes are different. The amplitude of the first autocorrelation pulse is still one, but that of the central peak is P^2, corresponding to all contributing elementary pulses adding up in phase. This represents an increase by a factor of P compared to the incoherent counterpart.

Conversely, we find that relatively less energy goes into the sidelobes of the autocorrelation. The ratio of sidelobes energy over peak energy is somewhat less than one in general. This makes it easier to discriminate between the peak and sidelobes for the purpose of thresholding, synchronization, etc.

Fig. 3 shows a simple example of an encoder connected to a decoder by a single fiber. Since there are two encoder outputs and two decoder inputs, there are several possibilities

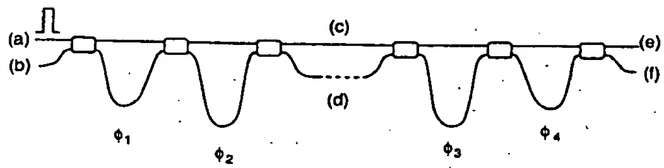


Fig. 3. Fiber-optic ladder encoder and decoder connected to each other.

to connect the two. We have shown that the design of the decoder to match a particular encoder depends upon how they are connected. Two possible connections have been shown, namely channels (c) and (d). It can be shown that a matched decoder can be found whether the decoder looks like the encoder, or its mirror image (case shown in Fig. 3). It turns out that the matched decoder phases are the same whether one uses either of the channels indicated.

To distinguish from what comes next, we refer to this type of matched decoding, wherein a single channel is used to link encoders and decoders, as single-channel or 1-channel coherent decoding.

VI. Coherent CDMA with Inverse Decoding

We first continue our presentation concerning coherent decoding in ladder networks, defining inverse decoding in these. We then relate this concept to work done with frequency components of pulses.

A. Ladder Networks

Continuing now with Fig. 3, we consider what happens if both channels (c) and (d) are used simultaneously, with no phase shift between them. We have shown that in that case the two autocorrelations in output (e) corresponding to these two paths have central peaks which add up in phase, with amplitude $4P^2$ (assuming ideal conditions, i.e., no excess losses, no phase or polarization mismatches). This is the total energy of the pulse initially fed into (a), and hence this network achieves perfect, lossless reconstruction of the initial pulse, which is clearly the best type of matched response that one can obtain. Another way to view the operation of this network in detail is that the couplers of the decoder and its phases are such that the pulses produced by the encoder are recombined by pairs until they eventually merge into a single pulse again. We refer to this type of coherent decoding, which clearly requires two channels to occur, as inverse decoding.

Some of the general properties of the three types of optical CDMA decoding are summarized in Table I. It is clear that coherent decoding can offer substantial advantages over incoherent decoding, and that inverse decoding represents the ultimate in decoder performance. Inverse decoding permits in principle lossless optical encoding/decoding, does away with sidelobes, and in fact provides a mechanism whereby transmission from a transmitter to a matched receiver occurs as if the encoding/decoding process did not take place, i.e., it is transparent to the user, in the sense that the received pulse is the same as if transmitter and receiver were linked by a standard broadcast network, without encoding/decoding. Indeed, from the point of view of matched inverse decoding, it does not matter how the detailed encoding/decoding is

TABLE I
Comparison of the Characteristics of the Various Possible Schemes for Optical CDMA

Scheme	Peak energy	Sides lobes
Incoherent	P	$P-1$
Coherent 1-channel	P^2	<1
Coherent 2-channel	$4\ P^2$	0

done, and as a result, one could in particular have bit periods shorter than the correlation sequence length $(2L-1)\tau_c$; with incoherent or 1-channel coherent operation this would not be possible as troublesome sidelobes would then overlap with the central peak.

While inverse decoding renders the matched response essentially ideal, the use of two channels probably does not have much to offer concerning the crosscorrelation with undesired signals. These will contribute noise as in 1-channel networks.

We also note another unique feature of inverse decoding: it allows for the simultaneous transmission of two bits. This is possible because when the decoder of Fig. 3 is the inverse of the encoder, not only are all pulses sent into (a) reconstructed in (e), but if we sent pulses into (b), they would emerge in (f). We thus have in effect two parallel, independent transmission lines, and we can make full use of the fact that we are using two fibers by doubling the link capacity, compared to 1-channel decoding. While the doubling of capacity can simply be attributed to having two parallel fibers, the fact that only a single set of encoder/decoder is needed distinguishes this system from other two-fiber systems.

B. Single Fiber Transmission for Stable Inverse Decoding

The use of two separate fibers as shown in Fig. 3 to connect encoders and decoders might be objected to on the basis that this will introduce phase drifts which would make the reconstruction process difficult to control. To alleviate this we have proposed and demonstrated the use of two orthogonal polarization states in a single fiber: the two channels become polarization channels, rather than spatial channels [19]. The two pulse trains are combined onto the fiber by means of a polarization beamsplitter, and separated likewise at the other end. In this manner, the two channels experience very nearly the same phase drifts, which cancel out. This approach is valid as long as the two polarizations remain orthogonal, which is the case as long as lossless components such as star couplers are used. Of course the polarization states change throughout the network unless polarization-preserving components are used; orthogonality of Jones vectors, however, is preserved in lossless components.

We note that here also we can transmit two bits at the same time through the system, even though a single fiber is used: We can make full use of the single transmission line used, by transmitting one bit stream on each orthogonal polarization.

C. Fabrication of Compact Encoders

As the pulse lengths get shorter, the physical size of the encoders should shrink in proportion. There are then several approaches available to make small, stable encoders.

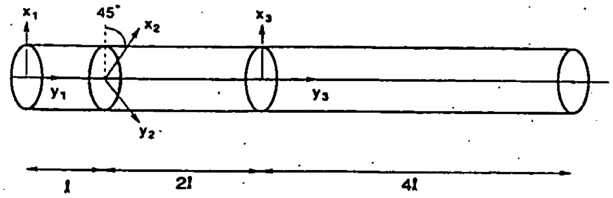


Fig. 4. Using rotated segments of polarization-preserving fiber to make stable encoders for coherent CDMA.

1) *Short fiber lengths:* With pulse lengths around 100 ps delays of several cm to tens of cm can be used. In this case we can still use the current approach using standard fibers arranged as in Fig. 2. Since only relative delays count, we can still work with standard couplers with reasonably long pigtails for handling. Phase adjustments can be made by means of PZT cylinders attached to the delay lines. After testing, the whole encoder assembly can be potted to increase stability.

2) *Integrated optics:* As pulses become very short, it may become difficult to control time delays accurately enough with the previous method. In that case integrated optics could offer an ideal solution. $LiNbO_3$ crystals up to 20 cm long can be used, providing total path delay of the order of 1 ns. Several stages of 3-dB couplers have been fabricated on such substrates, and similar technology could be used to make ladder networks. In fact, our requirements are essentially the same as those for concatenated Mach–Zehnder interferometers, recently demonstrated with seven stages for FDM demultiplexing [1].

3) *Polarization preserving fibers:* In the absence of integrated optical devices, there exists an alternate route to making stable encoders with short delays, with relative ease. This can be accomplished by replacing the two parallel fibers of the basic concept of Fig. 2 by two orthogonal polarization states in polarization preserving fibers (PPF's). Fig. 4 shows how this is done: the couplers of Fig. 2 are now replaced by end couplings between PPF fiber segments, rotated by 45° about their axis. The original input pulse is itself fed into the first segment at 45° with respect to its polarization axes. It splits into two pulses, one along each polarization axis, which propagate at different speeds due to the fiber birefringence. When the first one of these pulses reaches the next rotated fiber segment, it generates another two pulses along the new axes, and so does the second one, etc. Thus one can see that this arrangement performs exactly the same type of pulse train generation as the canonical arrangement of Fig. 2. A major advantage is that since a single fiber is now used, phase perturbations due to vibrations, thermal effects, etc., should largely cancel out, leading to a structure with potentially better stability than an integrated optic one. On the negative side, it will be more difficult to induce fine phase shifts by means of PZT's; they may have to be induced by applying stress perpendicular to the fiber, to affect the two polarizations differently.

The inverse of a PPF encoder can be found easily: it is the mirror image of the encoder (including the polarization axes), rotated by 90° about the axis of symmetry to exchange the polarization axes in all the segments. Clearly an encoder is not its own inverse.

This construction also holds for segments rotated by arbitrary angles (instead of the assumed 45° this provides additional degrees of freedom, namely pulse amplitudes, to generate more general codes sequences if desired. (This is equivalent to choosing coupling fractions in ladder networks which differ from 3 dB, a possibility which has also been considered [16].)

The design and manufacture of such PPF encoders will vary with pulse length, delays sought, fiber birefringence available. To keep mode matching losses down, it will be desirable to use fibers with a circular mode, and birefringence induced by stress members, rather than core shape. Concatenated segments of PPF's have been used in the past to make equal path nonlinear devices [20], as well as birefringent filters [21]. Hence accurate fabrication should be feasible.

We note that these single-fiber encoders are now a perfect match for the concept of a single-fiber transmission line to carry the signals from encoders to decoders. This makes the entire inverse decoding scheme conceptually, and potentially practically, quite simple. If a PPF network is used, it can begin at the last encoder interface, and continue to the first interface of the decoder; however, path lengths will have to be equalized by switching polarizations half way through the network; also a PPF star network would have to be used, and appropriately compensated. If a non-PPF network is used, as in our experiments to date, appropriate controllers will be needed to restore polarizations before the decoders.

Should equalization of the whole network prove too difficult in practice, the concept of PPF encoders can still be applied to 1-channel coherent decoding, even though some of the advantages of CDMA/ID would be lost.

D. Relation to work Using the Frequency Domain [22]

We have defined inverse decoding as that which restores exactly the shape of the original laser pulse. In this sense, it can also be found in work using manipulation of pulses in the frequency domain [22]. That approach is different from ours in that short pulses are dispersed into their frequency components by means of gratings, and the individual frequencies are phase shifted by means of phase screens. The operation is reversible, and indeed accurate reconstruction of subpicosecond pulses has been demonstrated in that manner. It has been shown that networks based on this approach have the potential for accommodating aggregate throughput in the range of 100 GHz, which would rival the demonstrated performance of FDM.

While our approach belongs to the same general scheme, there are some distinct advantages to it as we will see later, resulting from the fact that there are two inputs/outputs to our (de)coders.

VII. Comparison of WDM and CDMA with Inverse Decoding

WDM networks with aggregate throughput exceeding 1 Gb/s have been demonstrated [1]. It is thus important to examine under what conditions CDMA, particularly the coherent version with inverse decoding (CDMA/ID), might be able to rival it. Simple arguments will be used to bring out the

important points. Quantum noise is not considered as a first approximation, only cross-talk between signals.

Crosstalk in WDM has been studied in detail [23]; here we will present a simplified analysis to bring out the salient points. In WDM wavelength channels are separated at the receivers by filters such as Fabry–Perot etalons, or concatenated Mach–Zehnder interferometers. The filters' finesse F is the ratio of the total optical bandwidth used (free-spectral range) B_o to the bandwidth of each channel B_w, assuming that they are closely spaced. The filter is assumed to pass 100% of the signal at the peak of transmission, and the minimum transmittance at the rejected wavelengths is $1/F$. If K_w users are transmitting simultaneously toward different destinations, a receiver will receive its intended signal, as well as cross-talk from the rest. Let us take as a measure of signal to noise ratio the ratio of the intended power to the total crosstalk power, and denote it by R_w; it is given by

$$R_w = \frac{B_o}{K_w B_w} = \frac{B_o}{B_{tw}} \tag{1}$$

where B_{tw} is the aggregate bandwidth of the WDM network.

In the CDMA/ID network, we assume that K_c users are transmitting simultaneously, with individual bit rate B_c, for an aggregate bit rate $B_{tc} = K_c B_c$. The pulse width, or the time during which the detector is looking at it is τ_d. We now have a measure of the signal to noise ratio by taking the ratio of the energy in the peak of the autocorrelation, to the energy received from the nonmatched signal during τ_d. We find that

$$R_c = \frac{1}{K_c B_c \tau_d} = \frac{1}{B_{tc}\tau_d}. \tag{2}$$

From these results, we can write that

$$\frac{B_{tw}}{B_{tc}} = \left(\frac{R_w}{R_c}\right)\left(\frac{B_w}{B_c}\right) = B_o\tau_d; \tag{3}$$

to obtain the third expression it is assumed that $R_w = R_c$, which is a fair basis for comparing the two techniques. From this equation we see clearly on the right hand side the effect of the optical and electronic parameters: if the detection scheme is slow, then the RHS is a large number, and the LHS indicates that WDM will outperform CDMA overall, even though one may be able to achieve higher aggregate bit rate with CDMA, but only at the cost of much lower SNR. Clearly CDMA can compete with WDM only if the electronic detection (perhaps aided by nonlinear optics) can be accomplished very quickly, most likely in the picosecond range, as the optical bandwidth available for WDM is of the order of 1 THz. We note that this is indeed the regime of operation assumed by the Bellcore group [22].

With very short pulses, and a suitably fast detection scheme, CDMA/ID may thus be considered as a viable candidate for high-speed optical LAN's, with its own set of potential advantages over WDM, such as prospects for high stability and simple addressing. These points will be addressed in detail later.

In the above comparison, it has been assumed that the electronic receiver receives optical noise during a time τ_d which is greater than or equal to the chip time. If τ_d is large, CDMA cannot compete with WDM. In principle we can obtain a τ_d equal to the chip time, by using a nonlinear optical device, which suppresses all low-level noise, and lets through only the relatively higher spikes corresponding to autocorrelation, or inverse decoding. This will be discussed further.

We note that this nonlinear device acts as a time-dependent switch, or filter. In combination with the matched or inverse decoder, it plays in the time domain a role similar to that of the frequency filter in WDM. The nonlinear device limits the intensity reaching the detector during undesirable time periods, just as the wavelength filter attenuates the signals at undesirable frequencies.

The similarity between the WDM and CDMA approaches is interesting: both can utilize similar decoding or demultiplexing structures, namely concatened Mach–Zehnder interferometers. We also note that recently an alternative approach has been proposed for making WDM demultiplexers, wherein two single-mode star couplers are cascaded [24]. In this approach, fiber lengths can be adjusted to provide comb-like filter characteristics between each input and output port combination. We note that the physical structure of such an arrangement is again identical to that used by some to generate arbitrary code sequences for CDMA (e.g., Fig. 1).

These parallels suggest that WDM and CDMA can be viewed as complementary schemes using similar components, one in the time domain, the other in the frequency domain. In fact we have already begun to link the two in [19], as we have shown that the phase matching conditions required to obtain matching for the central peak of a correlation, for a pulse train consisting of a carrier of frequency ω modulated by an arbitrary envelope, are the same as for obtaining maximum transmission of the carrier if it were not modulated, i.e., as if it were the CW input assumed in WDM. Based upon the usual Fourier transform correspondence between the two domains, it should thus be possible to place the comparison between coherent CDMA and WDM on a more complete theoretical footing than the elementary one given above.

VIII. Advantages of Coherent CDMA with Ladder (De)coders

In the preceding section we have shown that under certain assumptions, coherent CDMA should be competitive with WDM. In this section we point to distinct advantages that coherent CDMA with ladder (de)coders has over WDM, and probably other networking schemes as well, and could indeed make CDMA the preferred approach under certain circumstances.

A. Two-Bit Wide Transmission

The operation of matched encoder-decoder pairs is such that if input a of an encoder is matched to output c of a decoder, then input b of the encoder is also matched with output d of the decoder. This permits the simultaneous, independent transmission of data streams on paths $a - c$ and $b - d$. [This is true whether one uses ID, or not.]

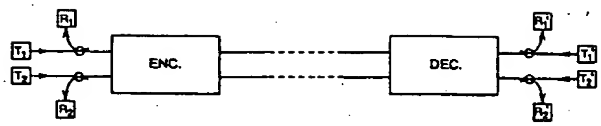


Fig. 5. Arrangement for obtaining double full-duplex communication with a single encoder-decoder set. The following transmitter-receiver pairs communicate: $T_1 - R_2, T_2 - R_2', T_1' - R_1$, and $T_2' - R_2$.

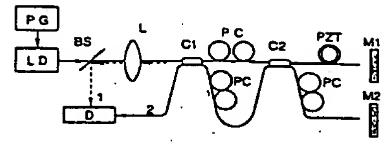


Fig. 6. Diagram of the single one-stage setup used to demonstrate coherent matched and inverse decoding. PG = pulse generator; LD = laser diode; BS = beam splitter; L = lens; D = detector; PC = polarization controller; C1, C2 = fiber couplers; PZT = piezoelectric transducer; M1, M2 = mirrors.

B. Bidirectional Transmission

It is clear that if an encoder is matched to a decoder for transmission in one direction, the match remains for transmission in the other direction as well. This in particular opens the possibility of having simultaneous transmission in opposite directions along $a - c$ and $b - d$. In this mode of operation, the pair of stations so linked can communicate in full duplex mode, Fig. 5. (And the link can be two-bit wide both ways, as indicated above.)

C. Balanced Detection

In Section VI the comparison between coherent CDMA and WDM was made on the basis of SNR in a single output channel, which is the only thing available in WDM. This comparison is actually unfair to CDMA, since in CDMA with ladder structures, there are actually two correlated outputs which can possibly be combined to improve overall SNR. In Section V we have already assumed that unmatched signals led to incoherent decoding, which yields the same result in the two outputs of a decoder; under those circumstances, if we have identical detectors in the two outputs, all unmatched signals will produce the same electronic noise at their outputs, which can then in principle be substracted to yield zero noise, while leaving the coherently detected matched signal untouched [25]. (This mode of operation probably precludes two-bit wide transmission, unidirectional or bidirectional, but the resulting benefit may be worth it.)

While the above reasoning is clearly an idealized limit, since obtaining zero noise is an impossibility, it nevertheless points to the potential for substantial noise reduction under the right circumstances.

IX. CDMA and Security

An area where CDMA should be much superior to WDM is in the area of confidentiality and security. It should be a relatively simple matter to tap a small fraction of the power travelling in a WDM fiber network, for instance by bending the fiber until light leaks out; by simply using a spectrometer, one should then be able to easily separate the channels, and obtain the information as AM modulation if no other safety precautions are taken. Trying to do the same on a fiber carrying CDMA signals should be more difficult, and could intentionally be made much harder.

Consider for instance a network operating with CDMA/ID. As mentioned earlier, due to the absence of sidelobes of the reconstructed bits, consecutive bits can follow each other separated by no delay. The coded bit length is $L\tau_c$, and so consecutive bits overlap over $(L - 1)\tau_c$. There is thus a large degree of overlap between consecutive bits, which should make it easy by introducing some level of higher level coding, such as Manchester, or MBNB, to ensure that even a single data stream from a single transmitter will always consist of highly overlapping codes. This will make it difficult to even decipher the basic location of the pulses associated with a single coded bit, the first step in breaking the code. If this could be done, however, the intruder would be in a position to build a decoder based on pulse spacings, and perform incoherent decoding; however, the presence of strong sidelobes in such decoding would make the decoded bits overlap strongly, probably rendering the output unintelligible. With determination, he could then try to achieve coherent decoding, or even inverse decoding. This, however, would require independently extracting light from each (of the two) channels, which should be rather difficult if they are carried as orthogonal polarization states in a birefringent fiber, finding the appropriate phase code for each, and combining the coherently-decoded outputs with appropriate phases to achieve ID.

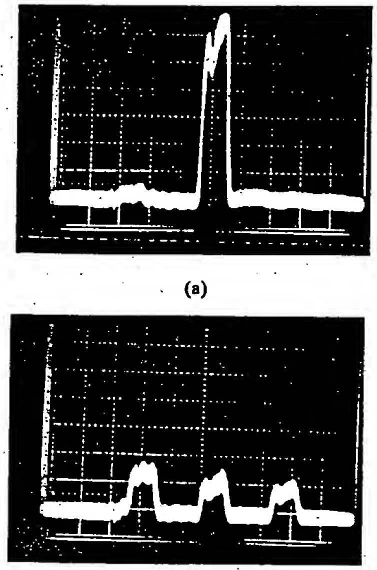
The frequency-domain CDMA approach also has useful security aspects. While it would be relatively straightforward to tap the single fiber carrying the data stream, finding the appropriate phase code to decode it would not be a very easy problem.

A combination of ladder and frequency-domain encoding could greatly increase the difficulty of deciphering optical signals tapped from such a network. Because the techniques are independent and cascadable, one could actually envision initially building a network with one technique, and later on upgrading it with the other if security requirements changed.

X. Experimental Demonstrations

To date some experimental work has been performed to show the feasibility of the concepts proposed for coherent CDMA.

In the first fiber study [16] a single stage ladder was used as shown in Fig. 6. Plain single-mode fiber was used. The 50-ns-long pulse from a laser was split by the ladder and emerged on two output fibers. Each fiber was terminated by a mirror, so that the energy was returned toward the ladder. By appropriate control of polarizations and phases, it was possible to control the interference to obtain inverse decoding in the input fiber not connected to the laser. Fig. 7(a) shows nearly ideal inverse decoding, whereas Fig. 7(b) shows a case where the phase difference is not adequate. In this experiment the stability was not very critical, because the decoder was the



(a)

(b)

Fig. 7. Results obtained with the setup of Fig. 6.: (a) inverse decoding, observed in fiber 1; (b) phase not suitable for inverse decoding.

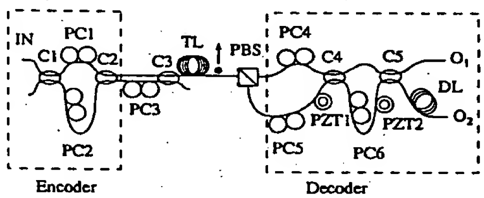
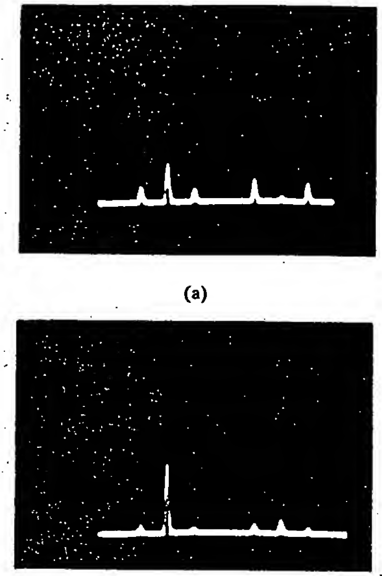


Fig. 8. Diagram of the double one-stage setup used to demonstrate coherent matched and inverse decoding with remote transmission from encoder to decoder. C1–C5 = 2 × 2 couplers; PC1–PC6 = polarization controllers; PZT1, PZT2 = piezoelectric phase shifters; TL = fiber transmission line; DL = delay line.

same as the encoder, and phase drifts due to the environment were automatically

In order to demonstrate the same effects under more realistic conditions we then undertook to use a decoder entirely separate from the encoder [19]. Again plain single-mode fiber was used. Fig. 8 shows the experimental setup. Here we implemented the idea of transmitting two separate channels on two orthogonal polarization states of the fiber: the two polarization states at the outputs of the encoder were rendered orthogonal by adjusting PC_1 and PC_2; they were then combined by C_3 (a 3 dB loss was incurred, compared to using a polarizing beam splitter; this was done for reason of cost); the two polarizations were then separated at the receiver by PBS. There was no active stabilization of the phases in the system, and it was far less stable than that of the first experiment. Nevertheless, with appropriate care and patience, it was possible to observe the desired results. When a single channel was used, we observed the expected 1-channel coherent autocorrelation, in both outputs; with proper phase relationship and using both channels, we also observed inverse decoding, as shown in Fig. 9. (Here the laser pulse duration was 30 ns.)



(a)

(b)

Fig. 9. Results obtained with the setup of Fig. 8.: (a) Waveforms at O_1 and O_2. respectively showing 1-channel autocorrelation and anticorrelation; (b) Waveforms at O_1 and O_2 for two-channel inverse decoding.

Related work with ladder networks has also been performed at the University of Kent [17], [18], [25]. The first investigation also used a single encoder/decoder to demonstrate 1-channel coherent autocorrelation and anticorrelation (corresponding to a vanishing central peak) [17]. The following step was to demonstrate coherent 1-channel decoding by a remote decoder [25]. That work was notable because a phase stabilization scheme was implemented, using an auxiliary dithering signal and thermal phase controllers; it was demonstrated that environmental phase drifts could be effectively tracked and cancelled, thereby proving that the use of phase-based schemes at optical frequencies is in fact viable. Another noteworthy feature is that balanced detection by substracting the two outputs of the decoder was proposed and demonstrated (the substraction, however, was not performed in real time, but with the average of stored signals). In all this work short pulses (100 ps) produced by laser diodes were used, thereby demonstrating compatibility with high-speed communication components.

Finally, an experiment showing the feasibility of coherent CDMA with inverse decoding based on frequency-domain encoding has been performed [22]. In that work, however, a single pair of gratings was used, and encoding and decoding phase masks were placed in contact between them. Remote decoding by a decoder distinct from the encoder has recently been demonstrated [27]; overall efficiency was only about 2%. Changing phase codes by means of liquid-crystal modulators could prove relatively simple in this approach [28].

XI. Discussion

Most of this paper has deal with physical-level aspects of optical CDMA networks, such as architecture, power budget, excess losses, phases, stability, signal-to-noise ratio, etc. We

have shown that ladder networks can provide the means of implementing high-speed multiple access LAN's, provided that coherent correlation is utilized. In particular we have seen that such networks can in principle rival WDM networks at very high data rates, provided that high-speed optical thresholding devices are available.

One aspect that we have not dealt with in detail is that of codes for optical CDMA. The reason is that while a considerable amount of work has been devoted to finding suitable codes for incoherent networks [8]–[10], [14], [29], the major obstacles discussed earlier to the practical implementation of such networks, make it unlikely that they will find widespread application. On the other hand since the field of coherent optical CDMA networks is quite young, little effort has been devoted to finding codes for it: to date only one study regarding phase codes for ladder networks has been reported [30]. This is an area which requires more work before the practical implementation of such networks can be considered. In this respect, it is interesting to note that if one considers codes with fixed pulse spacings, thus characterized only by phases [19], then one is actually in a situation very similar to phase- or polarization-modulation of CW optical (or rf) signals, for which phase codes have been studied; this may provide valuable insights for the study of coherent CDMA codes for ladder networks, much as existing phase codes were used for the study of frequency-domain encoding [22]. One common concern in CDMA is the ability to find enough codes to accommodate all potential users. Should either the ladder or frequency domain coding techniques fall short in that respect, the combination of the two may prove helpful.

XII. Future Prospects: Enhancing Coherent Optical CDMA

The current state of coherent optical CDMA, presented above, indicates some beneficial aspects, particularly in the area of security, but also some potential drawbacks, which can be traced to the need to use very short pulses. These are: 1) need for a short pulse laser (possibly fs); 2) dispersion of short pulses; 3) very short detection time assumed, possibly requiring a nonlinear optical threshold.

All three of these drawbacks can be remedied by considering the novel arrangement of Fig. 10; it constitutes a refinement of compensation techniques recently proposed [31]. In this basic form, it requires two parallel channels, C_1 and C_2, which may take the form of two parallel fibers, or two orthogonal polarization states in a single fiber. The idea is to use C_1 to carry a reference pulse R, and C_2 a coded sequence A. The decoder produces an impulse response B when R reaches it. The last 2×2 coupler is such that signals proportional to $(A+B)$ and $(A-B)$ appear at its outputs. The detectors have a square-law characteristic, so that their respective outputs are proportional to $(A+B)^2$ and $(A-B)^2$. By connecting the detectors as shown, the combined output of the detectors, S, is equal to their difference, i.e., $S=(A+B)^2-(A-B)^2=4AB$ (at each instant of time). S is then integrated over a bit time by the integrator; if the optical path lengths of C_1 and C_2 are properly adjusted, then the result of the integration is proportional to the crosscorrelation of A and B, evaluated

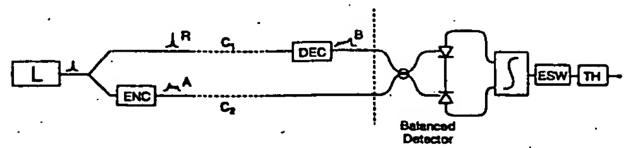


Fig. 10. Two channel scheme to transmit a reference pulse along with the encoded signal. L = laser; ENC = encoder; DEC = decoder; ∫ = time integrator; ESW = electronic switch; TH = threshold.

at zero delay. This system can thus perform temporal pattern recognition by comparing the values of correlations with no delays, if we just place a comparator after the dumping switch. It should be noted that this scheme is a coherent one, as A and B are field amplitudes, and not powers.

Because A and R both travel along essentially identical paths, A and B will be affected similarly if chromatic dispersion is present in the channels; hence recognition will still occur in much the same manner as if there was essentially no dispersion.

This approach is similar to coherent detection in WDM, and with it it shares the possibility of achieving lower crosstalk between channels than if simple filtering and direct detection were used.

Because the comparison of electrical signals can now take place on the time scale of the bit time, rather than τ_c in conventional optical CDMA, one can use conventional electronic thresholding even at relatively high data rates, up to several gigabits-per-second. Also, because there is no need to detect the exact temporal shape of the waveform AB, the optical detectors do not have to have response times below τ_c; somewhat below the bit time would suffice. Again this relieves the constraints on the optoelectronic components.

A final advantage is that since there is no need to actually reconstruct a very short optical pulse for detection, we could actually use a relatively long one. For instance, a broadband, fairly long laser pulse could be used, and encoded by a frequency domain technique. What counts here is that the matched signal will be recognized just as well for a long or very short laser pulse. The only difference might occur in the discrimination against unwanted or unmatched signals, for which the shape of the initial laser pulse might make a difference. In this regime, it might be fruitful to think of the encoding mechanism as one of coherence multiplexing [32]; in other words, a match will occur only if two signals are coherent. Basically, the laser pulse duration could be of the order of the bit time, but its coherence time should be of the order of τ_c; this requirement is much easier to satisfy than having transform-limited pulses of the order of τ_c themselves.

This approach utilizes the best aspect of optics and electronics: passive optics, with extremely high-speed are used to encode and decode the laser pulses; on the other hand relatively slow optoelectronic and electronic components are used to perform the integration, final thresholding, as well as laser modulation.

A method to eliminate potential phase drifts between two parallel channels, is to use a single channel, in which the signals are sent one after the other. The method is in fact similar to what is done in differential phase shift keying

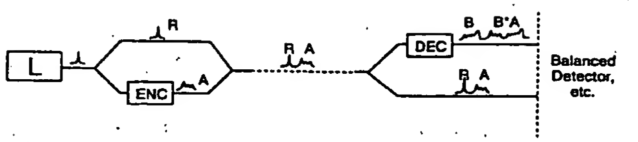


Fig. 11. Single-channel scheme to transmit a reference pulse along with the encoded signal.

(DPSK). A delay line is required at the transmitter to delay one signal with respect to the other, and another one is required at the receiver. For proper coherent operation, the phases of these two delay lines will have to be kept nearly equal. There are several approaches to physically superimposing the two signals on the same channel; Fig. 11 shows a version using permanent 3-dB couplers.

This novel technique is compatible with either ladder or frequency-domain phase encoding. It can potentially be used to enhance the features of coherent optical CDMA, by removing aspects previously viewed as being inferior to those of WDM systems, while preserving the major aspect of security. It is anticipated that this type of development will be representative of future work in coherent optical CDMA.

XIII. Conclusion

The recent work in optical CDMA has been reviewed, and it has been argued that the incoherent approach does not look promising because of the great difficulty of reconfiguring the encoder every time that the destination address needs to be changed. Studying then the potential of coherent CDMA, it has been shown that it can rival WDM in terms of aggregate network throughput, provided that either very short pulses are used (in the picosecond range), and that a fast nonlinear-optic threshold device is used before the detector, or that a reference pulse is sent along with the encoded pulse. Concerning ladder-network encoders and decoders, their complexity is similar to that of tuned filters used in WDM, indicating an interesting convergence of hardware requirements for WDM and CDMA. Coherent CDMA thus appears as a viable candidate to implement some of the high-speed networks which will be required in the future. By its nature it has inherent security aspects which could prove advantageous in applications where it is desirable to have substantial security introduced at the physical level.

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References

[1] H. Toba *et al.*, "A 100-channel optical FDM transmission distribution at 622 Mb/s over 50 km," *J. Lightwave Technol.*, vol. 9, pp. 1396–1400, 1990, N. Takato *et al.*, "128-channel polarization-insensitive frequency-selection switch using high-silica waveguides on Si," *IEEE Photon. Technol. Lett.*, vol. 2, pp. 441–443, 1990.

[2] K. Wilner and A. P. Van den Heuvel, "Fiber-optic delay lines for microwave signal processing," *Proc. IEEE*, vol. 64, pp. 805–807, 1976.

[3] R. L. Ohlhaber and K. Wilner, "Fiber optic delay lines for pulse coding," *Electro-Optical Syst. Des.*, pp. 33–35, 1977.

[4] E. Marom, "Optical delay lines matched filters," *IEEE Trans. Circ. Syst.*, vol. CAS-25, pp. 360–364, 1978.

[5] K. P. Jackson *et al.*, "Optical fiber delay-line signal processing," *IEEE Trans. Micr. Theory and Tech.*, vol. MTT-33, pp. 193–210, 1985.

[6] S. Gweon, Ç. E. Lee, and H. F. Taylor, "Programmable fiber optic signal processor," *IEEE Photon. Technol. Lett.*, vol. 2, pp. 382–384, 1990.

[7] See for example *IEEE J. Select. Areas Commun.*, vol. 10, May 1992, special issue on spread spectrum.

[8] J. A. Salehi and C. A. Brackett, "Code division multiple-access techniques in optical fiber networks-Part II: Systems performance analysis," *IEEE Trans. Commun.*, vol. 37, pp. 834–842, 1990.

[9] P. R. Prucnal, M. A. Santoro, and T. R. Fan, "Spread spectrum fiber-optic local area network using optical processing," *J. Lightwave Technol.*, vol. LT-4, pp. 547–554, 1986.

[10] Y. L. Chang and M. E. Marhic, "2" Codes for Optical CDMA and associated networks," *IEEE Topical Meeting on Optical Multiple Access Networks* (Monterey, CA), July 25–27, 1990.

[11] Y. L. Chang, "Optical codes for fiber networks," Ph.D. dissertation, Northwestern Univ., Evanston, Il, Sept. 1990.

[12] A. S. Holmes and R. R. A. Syms, "Switchable all-optical encoding and decoding using optical fiber lattices," *Opt. Comm.*, vol. 86, pp. 25–28, 1991.

[13] J. Y. Hui, "Pattern code modulation and optical decoding - A novel code-division multiplexing for multifiber networks," *IEEE J. Select. Areas Commun.*, vol. SAC-3, pp. 916–927, 1985.

[14] A. J. Mendez, S. Kuroda, R. Gagliardi, and E. Garmire, "Generalized temporal code division multiple access (CDMA) for optical communications," *Proc. of SPIE*, vol. 1175, pp. 208–217, 1989.

[15] E. Park, A. J. Mendez, and E. Garmire, "Temporal/spatial optical CDMA networks - Design, demonstration and comparison with temporal networks," *IEEE Photon. Technol. Lett.*, vol. 4, pp. 1160–1162, 1992.

[16] M. E. Marhic and Y. L. Chang, "Pulse coding and coherent decoding in fiber optic ladder networks," *Electron. Lett.*, vol. 25, pp. 1535–1536, 1989.

[17] D. D. Sampson and D. A. Jackson, "Coherent optical fiber communications system using all-optical correlation processing," *Opt. Lett.*, vol. 15, pp. 585–587, 1990.

[18] D. D. Sampson and D. A. Jackson, "Spread-spectrum optical fibre network based on pulsed coherent correlation," *Electron. Lett.*, vol. 26, pp. 1550–1552, 1991.

[19] Y. L. Chang and M. E. Marhic, "Fiber-optic ladder networks for inverse decoding coherent CDMA," *J. Lightwave Technol.*, vol. 10, 1992.

[20] T. Morioka and M. Saruwatari, "All-optical ultrafast nonlinear switching utilizing the optical Kerr effect in optical fibers," *Opt. Eng.*, vol. 29, pp. 200–209, 1990.

[21] M. Johnson, "Single-mode-fiber birefringent filters," *Opt. Lett.*, vol. 5, pp. 142–144, 1980.

[22] J. A. Salehi, A. M. Weiner, and J. P. Heritage, "Coherent ultrashort light pulse code-division multiple access communication systems," *J. Lightwave Technol.*, vol. 8, pp. 478–491, 1990.

[23] P. A. Humblet and W. M. Hamdy, "Crosstalk analysis and filter optimization of single- and double-cavity Fabry–Perot filters," *IEEE J. Select. Areas Commun.*, vol. 8, pp. 1095–1107, 1992.

[24] C. Dragone, C. A. Edwards, and R. C. Kistler, "Integrated optics $N \times N$ multiplexer on silicon," *IEEE Photon. Technol. Lett.*, vol. 3, pp. 896–899, 1991.

[25] R. A. Griffin, D. D. Sampson, and D. A. Jackson, "Demonstration of data transmission using correlation to reconstruct a coded pulse sequence," *IEEE Photon. Tech. Lett.*, vol. 4, pp. 513–515, 1992.

[26] A. M. Weiner *et al.*, "Recent advances in ultrashort optical pulse shaping for high-speed communications," *IEEE Topical Meet. Optical Multiple Access Networks* (Santa Barbara, CA), Aug. 3–5, 1992, paper TuC1.

[27] P. L. Chua, J. L. Lambert, J. M. Morookian, and L. A. Bergman, "Optical protocols for terabit networks," *IEEE Topical Meet. Optical Multiple Access Networks* (Santa Barbara, CA), Aug. 3–5, 1992, paper TuC2.

[28] A. M. Weiner, D. E. Leaird, J. S. Patel, and J. R. Wullert, "Programmable femtosecond pulse shaping by use of a multielement liquid-crystal phase modulator," *Opt. Lett.*, vol. 15, pp. 326–328, 1990.

[29] A. S. Holmes and R. R. A. Syms, "All-optical CDMA using "quasi-prime" codes," *J. Lightwave Technol.*, vol. 10, pp. 279–286, 1992.

[30] R. A. Griffin, D. D. Sampson, R. F. de Caleya, and D. A. Jackson, "Reconfigurable code-division multiple-access network, using optical phase codes," *OE/FIBERS '92* (Boston, MA), Sept. 8–11, 1992.

[31] M. E. Marhic, "Trends in optical CDMA," *OE/FIBERS '92* (Boston, MA), Sept. 8–11, 1992.

[32] J.-P. Goedgebuer, A. Hamel, and H. Porte, "Full bidirectional fiber transmission using coherence-modulated lightwaves," *IEEE J. Quantum Electron.*, vol. 28, pp. 2685–2691, 1992.

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